



TITLE:

CURVE COMPLEXES AND THE DM-COMPACTIFICATION OF MODULI SPACES OF RIEMANN SURFACES (Topology, Geometry and Algebra of low-dimensional manifolds)

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CITATION:

松本, 幸夫. CURVE COMPLEXES AND THE DM-COMPACTIFICATION OF MODULI SPACES OF RIEMANN SURFACES (Topology, Geometry and Algebra of low-dimensional manifolds). 数理解析研究所講究録 2016, 1991: 109-116: KJ00010218668.

ISSUE DATE:

2016-04

URL:

<http://hdl.handle.net/2433/224623>

RIGHT:

CURVE COMPLEXES AND THE DM-COMPACTIFICATION OF MODULI SPACES OF RIEMANN SURFACES

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1. INTRODUCTION

Let $M_{g,n}$ be the moduli space of Riemann surfaces of genus g with n punctures. In this report, we study the DM (=Deliene-Mumford) compactification $\overline{M}_{g,n}$ of $M_{g,n}$. Our purpose is three-fold: (1) to construct a “natural” atlas of orbifold-charts on $\overline{M}_{g,n}$, making use of N. V. Ivanov’s “scissored Teichmüller space” $P_{g,n}^\varepsilon$ [9], (2) to clarify the role of W. J. Harvey’s curve complex $\mathcal{C}_{g,n}$ [7] in the compactification process, and finally (3) to point out a natural connection between Teichmüller spaces and crystallographic groups.

2. BASIC DEFINITIONS

We consider a pair (S, w) of a Riemann surface S and an orientation preserving homeomorphism $w : \Sigma_{g,n} \rightarrow S$, where $\Sigma_{g,n}$ is an oriented surface of type (g, n) . Two such pairs (S, w) and (S', w') are *equivalent* $(S, w) \sim (S', w')$ if and only if there exists a biholomorphic map $t : S \rightarrow S'$ such that the following diagram homotopically commutes:

$$\begin{array}{ccc} \Sigma_{g,n} & \xrightarrow{w} & S \\ \text{id.} \downarrow & & \downarrow t \\ \Sigma_{g,n} & \xrightarrow{w'} & S'. \end{array}$$

The *Teichmüller space* $T_{g,n}$ is defined by

$$T_{g,n} = \{(S, w)\} / \sim.$$

We denote the mapping class group of $\Sigma_{g,n}$ by $\Gamma_{g,n}$, and define its action on $T_{g,n}$ by

$$[f]_*[S, w] = [S, w \circ f^{-1}],$$

where $[f] \in \Gamma_{g,n}$ and $[S, w] \in T_{g,n}$.

$T_{g,n}$ is a complex analytic space ([22], [3]), and is a bounded domain [4] of $\dim_{\mathbb{C}} T_{g,n} = 3g - 3 + n$.

We define the *length function* $L : T_{g,n} \rightarrow \mathbb{R}$ as follows: Let C be an essential simple closed curve on $\Sigma_{g,n}$. For any point $p = [S, w] \in T_{g,n}$, let $l_p(C)$ be the length of the simple closed geodesic \hat{C} on S homotopic to $w(C)$. Define $L : T_{g,n} \rightarrow \mathbb{R}$ by

$$L(p) \stackrel{\text{def.}}{=} \min_{C \subset \Sigma_{g,n}} l_p(C).$$

The length function L is a piecewise real analytic function on $T_{g,n}$ (Fenchel-Nielsen, Abikoff [2]).

3. IVANOV'S SCISSORED TEICHMÜLLER SPACE $P_{g,n}^\varepsilon$

Let $\varepsilon > 0$ be a sufficiently small number. In his cohomological study on the mapping class groups, N. V. Ivanov [9] introduced the following space, which we would like to call *Ivanov's scissored Teichmüller space* and to denote by $P_{g,n}^\varepsilon$:

$$P_{g,n}^\varepsilon \stackrel{\text{def.}}{=} \{p \in T_{g,n} \mid L(p) \geq \varepsilon\}.$$

$P_{g,n}^\varepsilon$ is a real analytic manifold with corners. (The author was pointed out by Hiroshige Shiga that $P_{g,n}^\varepsilon$ is usually known as a *thick part* of $T_{g,n}$.)

To what extent should ε be small? To answer this question, let us recall the following

Theorem 3.1. (*Keen [12], Abikoff [2]*) *There is an universal constant M such that two distinct simple closed geodesics on S are disjoint, if their lengths are smaller than M .*

The number ε should be taken as $\varepsilon < M$.

3.1. Facets of $P_{g,n}^\varepsilon$. Suppose a point $p_0 = [S_0, w_0]$ is on the boundary $\partial P_{g,n}^\varepsilon$ of $P_{g,n}^\varepsilon$, then we have

$$L(p_0) = \varepsilon.$$

There exist a finite number of simple closed curves

$$C_1, \dots, C_k$$

on $\Sigma_{g,n}$ such that $l_{p_0}(C_i) = \varepsilon$, $i = 1, \dots, k$. (Recall this means that the geodesics \hat{C}_i have hyperbolic length ε on S_0 , where \hat{C}_i is the simple closed geodesic homotopic to $w_0(C_i)$, $i = 1, \dots, k$.) The geodesics $\hat{C}_1, \dots, \hat{C}_k$ are disjoint, because $\varepsilon < M$, and we may assume that C_1, \dots, C_k are disjoint on $\Sigma_{g,n}$. We have

$$k \leq 3g - 3 + n,$$

because $3g - 3 + n$ is the maximum number of the simple closed curves on $\Sigma_{g,n}$ which are essential, disjoint, and mutually non-isotopic.

Let σ be the set of these simple closed curves on $\Sigma_{g,n}$:

$$\sigma = \{C_1, \dots, C_k\}.$$

Define the facet $F^\varepsilon(\sigma)$ corresponding to σ by

$$F^\varepsilon(\sigma) = \{p \in P_{g,n}^\varepsilon \mid l_p(C_i) = \varepsilon, i = 1, \dots, k\}.$$

For all points $p = [S, w]$ on $F^\varepsilon(\sigma)$, we assume that other simple closed geodesics on S have length greater than ε . (The point p_0 is on this facet.)

In general, for any set σ of essential, disjoint, and mutually non-isotopic simple closed curves on $\Sigma_{g,n}$, the corresponding facet $F^\varepsilon(\sigma)$ is a real analytic manifold homeomorphic to

$$\mathbb{R}^{2(3g-3+n)-k},$$

where $k = \#\sigma$. Facets are analogous to open faces of a finite polyhedron.

Here is an incidence relation: If $\sigma \subset \sigma'$, then we have

$$\overline{F^\varepsilon(\sigma)} \supset F^\varepsilon(\sigma').$$

If $\#\sigma < 3g - 3 + n$, the facet $F^\varepsilon(\sigma)$ is surrounded by an infinite number of facets. Thus in this case, a facet is itself an infinite polyhedron.

3.2. Abelian subgroups $\Gamma(\sigma)$. Let σ denote $\{C_1, \dots, C_k\}$ as before. Let $\tau(C_i)$ be the right handed (i.e. negative) Dehn twist about C_i , and define $\Gamma(\sigma)$ to be the subgroup of $\Gamma_{g,n}$ generated by

$$\tau(C_i), \quad i = 1, \dots, k.$$

The group $\Gamma(\sigma)$ is a free abelian group of rank k . Since the action of $\Gamma_{g,n}$ on $T_{g,n}$ preserves the Poincaré metric on Riemann surfaces (hence preserves the length function L), and

$$\tau(C_i)(C_j) = C_j, \quad i, j = 1, \dots, k,$$

the twists $\tau(C_i)$ preserve $F^\varepsilon(\sigma)$. This action of $\Gamma(\sigma)$ on $F^\varepsilon(\sigma)$ is real analytic and properly discontinuous.

4. COMPLEX OF CURVES AND $P_{g,n}^\varepsilon$

W. J. Harvey (1977) [7] introduced an abstract simplicial complex called the *complex of curves* $\mathcal{C}_{g,n} = \mathcal{C}(\Sigma_{g,n})$:

Definition 4.1. A *vertex* of $\mathcal{C}_{g,n}$ is an isotopy class of an essential simple closed curve on $\Sigma_{g,n}$, and a *simplex* σ of $\mathcal{C}_{g,n}$ is a set of vertices represented by a disjoint union of essential simple closed curves which are mutually non-isotopic.

Facets $F^\varepsilon(\sigma)$ are in one-to-one correspondence with the simplices σ of $\mathcal{C}_{g,n}$.

Proposition 4.2. *The totality of the facets $\{F^\varepsilon(\sigma)\}_{\sigma \in \mathcal{C}_{g,n}}$ makes a complex (facet complex) analogous to a simplicial complex. The flag complex associated with the facet complex is isomorphic to the barycentric subdivision of the complex of curves $\mathcal{C}_{g,n}$.*

Proof. A flag in the facet complex $\overline{F^\varepsilon(\sigma)} \supset \overline{F^\varepsilon(\sigma')} \supset F^\varepsilon(\sigma'')$ corresponds to a flag in the complex of curves $\mathcal{C}_{g,n}$, $\sigma \subset \sigma' \subset \sigma''$. The latter corresponds to a simplex of the barycentric subdivision of $\mathcal{C}_{g,n}$. \square

4.1. Automorphisms of $\mathcal{C}_{g,n}$. We need the following theorem:

Theorem 4.3. (Ivanov [10], Korkmaz [13], Luo [15]) *Except for a few sporadic cases (spheres with ≤ 4 punctures, tori with ≤ 2 punctures and a closed surface of genus 2), the following holds:*

$$\text{Aut}(\mathcal{C}_{g,n}) = \Gamma_{g,n}^*,$$

where $\Gamma_{g,n}^*$ stands for the extended mapping class group (containing orientation reversing homeomorphisms).

The scissored Teichmüller space $P_{g,n}^\varepsilon$ together with the Teichmüller metric becomes a metric (infinite) polyhedron. The following proposition is a corollary to the above theorem:

Proposition 4.4. *With the same exceptions as above, we have*

$$\text{Isom}_+(P_{g,n}^\varepsilon) = \Gamma_{g,n}.$$

Proof. An isomorphism of $P_{g,n}^\varepsilon$ induces on $\partial P_{g,n}^\varepsilon$ an automorphism of the facet complex, thus that of the barycentric subdivision of $\mathcal{C}_{g,n}$, and finally an automorphism of $\mathcal{C}_{g,n}$. The automorphism of $\mathcal{C}_{g,n}$ in turn corresponds (by Ivanov-Korkmaz-Luo's theorem) to an action of the mapping class group $\Gamma_{g,n}$, hence an (orientation preserving) isometry of $T_{g,n}$. \square

Essentially the same arguments have been done in Papadopoulos [21] and Ohshika [20].

Proposition 4.5. *The subgroup of $\Gamma_{g,n}$ which preserves a facet $F_{g,n}^\varepsilon$ is precisely $NT(\sigma)$, the normalizer of $\Gamma(\sigma)$ in $\Gamma_{g,n}$.*

Proof. If a mapping class $[f] \in \Gamma_{g,n}$ preserves $F_{g,n}^\varepsilon$, then $[f]$ induces on $\Sigma_{g,n}$ a permutation of $\sigma = \{C_1, \dots, C_k\}$, and *vice versa*. Such mapping classes form the normalizer $NT(\sigma)$ of $\Gamma(\sigma)$. \square

4.2. “Fringe” $FR^\varepsilon(\sigma)$ bounded by $F^\varepsilon(\sigma)$. The fringe $FR^\varepsilon(\sigma)$ is defined by

$$FR^\varepsilon(\sigma) = \bigcup_{0 < \delta < \varepsilon} F^\delta(\sigma).$$

Then we have

Corollary 4.6. *The subgroup of $\Gamma_{g,n}$ which preserves the fringe $FR^\varepsilon(\sigma)$ is the normalizer $NT(\sigma)$. The action of $NT(\sigma)$ on $FR^\varepsilon(\sigma)$ is properly discontinuous.*

Proof. $FR^\varepsilon(\sigma)$ is foliated by the facets $F^\delta(\sigma)$, and the corollary holds for each leaf $F^\delta(\sigma)$. \square

Define the *augmented fringe* as follows:

$$\overline{FR^\varepsilon(\sigma)} = \bigcup_{0 \leq \delta < \varepsilon} F^\delta(\sigma) (= FR^\varepsilon(\sigma) \sqcup F^0(\sigma)).$$

$NT(\sigma)$ acts on $\overline{FR^\varepsilon(\sigma)}$ continuously, but *not* properly discontinuously, because the infinite subgroup $\Gamma(\sigma) (\subset NT(\sigma))$ fixes the points of the added ideal boundary $F^0(\sigma)$. Abikoff[1] attached to $T_{g,n}$ all ideal boundaries, and considered the *augmented Teichmüller space*

$$\overline{T}_{g,n} = T_{g,n} \sqcup \bigcup_{\sigma \in \mathcal{C}_{g,n}} F^0(\sigma).$$

Yamada [24] identified $\overline{T}_{g,n}$ with the Weil-Petersson completion of $T_{g,n}$, and proved the geodesic convexity of the ideal boundaries $F^0(\sigma)$. It is well-known that the quotient space of $\overline{T}_{g,n}$ under the action of $\Gamma_{g,n}$ is the compactified moduli space $\overline{M}_{g,n}$. Note that the union of the augmented fringes $\bigcup_{\sigma \in \mathcal{C}_{g,n}} \overline{FR^\varepsilon(\sigma)}$ gives an open neighborhood of the singular divisors when divided out by the action of $\Gamma_{g,n}$.

5. CONTROLLED DEFORMATION SPACES

To analyse the orbifold structure of $\overline{M}_{g,n}$, the fringes $\overline{FR^\varepsilon(\sigma)}$ are not necessarily adequate, because they are *pairwise disjoint*:

$$\overline{FR^\varepsilon(\sigma)} \cap \overline{FR^\varepsilon(\sigma')} = \emptyset, \quad \text{if } \sigma \neq \sigma'.$$

(Recall that the facets are like open faces of a polyhedron.) Namely the fringes do not make an open covering of the singular divisors $\bigcup_{\sigma \in \mathcal{C}} F^0(\sigma)$.

To remedy the deficiency, we introduce *controlled deformation spaces*. But before going to them, let us recall *Bers’ deformation spaces*.

Let $\sigma \in \mathcal{C}_{g,n}$ be any simplex $\sigma = \{C_1, \dots, C_k\} \in \mathcal{C}_{g,n}$. Let $\Sigma_{g,n}(\sigma)$ denote the surface with nodes obtained by pinching each C_i ($\in \sigma$) in $\Sigma_{g,n}$ to a point. Bers [5] introduced the *deformation space* $D(\sigma)$ associated with $\Sigma_{g,n}(\sigma)$. The following fact is known:

Proposition 5.1. *(See Kra [14] §9, Matsumoto [18] §6.) $D(\sigma)$ is homeomorphic to $(T_{g,n}/\Gamma(\sigma)) \cup \bigcup_{i=1}^k \Pi_i$, where $\Pi_i = \mathbb{C}^{i-1} \times \{0\} \times \mathbb{C}^{3g-3+n-i}$, and $\bigcap_{i=1}^k \Pi_i$ corresponds to F^0 .*

(Π_i is mentioned as a “distinguished subset” in Bers [5].) Bers announced in 1970’s that $D(\sigma)$ is a bounded domain (see [5]), but without proof. Recently, Hubbard and Koch [8] gave a proof.

Theorem 5.2. *The deformation space $D(\sigma)$ is a complex manifold of $\dim_{\mathbb{C}} = 3g - 3 + n$.*

Their arguments are a little bit complicated, but the geometry is conceptually clear. The space $F^0(\sigma)$ is the Teichmüller space of the nodal surface $\Sigma_{g,n}(\sigma)$ and serves as the “core” of $D(\sigma)$ (Masur [17]). It is thickened in the transverse direction by the “plumbing coordinates” (Marden [16], Earle and Marden [6]).

5.1. The groups $W(\sigma)$. Define

$$W(\sigma) = N\Gamma(\sigma)/\Gamma(\sigma).$$

The groups $W(\sigma)$ are not finite groups in general.

Proposition 5.3. (i) $W(\sigma)$ is the mapping class group of the nodal surface $\Sigma_{g,n}(\sigma)$.
(ii) $W(\sigma)$ acts on $D(\sigma)$ holomorphically and properly discontinuously.

5.2. Controlled deformation spaces. Let M be a constant of Keen and Abikoff. We take an ε satisfying $0 < \varepsilon < M$. We insert $6g - 6 + 2n$ numbers between ε and M :

$$\varepsilon < \varepsilon_1 < \eta_1 < \cdots < \varepsilon_{3g-3+n} < \eta_{3g-3+n} < M.$$

Let $\hat{\varepsilon}$ denote this sequence. We define the *controlled deformation space* $D_{\hat{\varepsilon}}(\sigma)$ as follows (σ being $\{C_1, \dots, C_k\}$):

$$D_{\hat{\varepsilon}}(\sigma) = \{p = [S, w] \in D(\sigma) \mid l_p(C_i) < \varepsilon_k, \quad i = 1, \dots, k, \\ \text{and other simple closed geodesics on } S \text{ are longer than } \eta_k\}$$

Why do we need the controlled deformation spaces $D_{\hat{\varepsilon}}(\sigma)$? Because Bers’ deformation spaces $D(\sigma)$ do not naturally descend to $\overline{M}_{g,n}$, but $D_{\hat{\varepsilon}}(\sigma)$ do. For a proof of this fact, see [18], §7

Proposition 5.4. (i) $D_{\hat{\varepsilon}}(\sigma)$ is a bounded domain of \mathbb{C}^{3g-3+n} .
(ii) The group $W(\sigma)$ acts on $D_{\hat{\varepsilon}}(\sigma)$ holomorphically and properly discontinuously.
(iii) $D_{\hat{\varepsilon}}(\sigma)/W(\sigma)$ is an open subset of $\overline{M}_{g,n}$.
(iv) $D_{\hat{\varepsilon}}(\sigma)/W(\sigma)$ contains the “main part” of the quotient of the augmented fringe $\overline{FR^{\varepsilon}}(\sigma)/W(\sigma)$.
(v) The family $\{D_{\hat{\varepsilon}}(\sigma)/W(\sigma)\}_{\sigma \in \mathcal{C}_{g,n}}$ is an open covering of the “boundary” singular divisors $\bigcup_{\sigma \in \mathcal{C}_{g,n}} F^0(\sigma)/\Gamma_{g,n}$.

Summarizing the above, we have our main theorem:

Theorem 5.5. (Matsumoto [18]) *The family $\{(D_{\hat{\varepsilon}}(\sigma), W(\sigma))\}_{\sigma \in \mathcal{C}_{g,n}}$ gives orbifold-charts containing the boundary singular divisors in $\overline{M}_{g,n}$.*

Remark 5.6. If $\sigma' = f(\sigma)$ by a mapping class $[f] \in \Gamma_{g,n}$, we consider that $(D_{\hat{\varepsilon}}(\sigma), W(\sigma))$ and $(D_{\hat{\varepsilon}}(\sigma'), W(\sigma'))$ are the identical charts. Thus the index set of the family of charts is actually $\mathcal{C}_{g,n}/\Gamma_{g,n}$.

6. CRYSTALLOGRAPHIC GROUPS

Definition 6.1. A *crystallographic group* in Euclidean m -space \mathbb{E}^m is a group G of isometries of \mathbb{E}^m whose translation vectors form a lattice $L \subset \mathbb{E}^m$.

The image of G under linearization $Isom(\mathbb{E}^m) \rightarrow O(\mathbb{E}^m)$ is called the *point group* of G and denoted by \vec{G} . This is a finite group. There is a canonical exact sequence

$$1 \rightarrow T \rightarrow G \rightarrow \vec{G} \rightarrow 1,$$

where T is the translation subgroup of G . See [11].

6.1. Crystallographic groups in Teichmüller theory. For simplicity, we consider a closed surface Σ_g (i.e. $n = 0$), and in what follows, we assume that σ is a maximal simplex of \mathcal{C}_g , i.e., $\sigma = \{C_i\}_{i=1, \dots, 3g-3}$. Then the group $W(\sigma)$ is finite. In this case, the facet $F^\varepsilon(\sigma)$ is defined by

$$l_i = \varepsilon, \quad i = 1, \dots, 3g - 3$$

by the Fenchel-Nielsen coordinates associated with σ ,

$$(l_i, \tau_i), \quad i = 1, \dots, 3g - 3.$$

By Wolpert's formula, the Weil-Petersson symplectic form is written as follows:

$$\omega_{WP} = \frac{1}{2} \sum_i dl_i \wedge d\tau_i.$$

We see $\omega_{WP}|_{F^\varepsilon(\sigma)} = 0$, thus $F^\varepsilon(\sigma)$ is a *Lagrangian submanifold* of $\dim_{\mathbb{R}} = 3g - 3$.

$F^\varepsilon(\sigma)$ is homeomorphic to \mathbb{R}^{3g-3} on which $\Gamma(\sigma)$ acts as translations. The action of $NT(\sigma)$ on $F^\varepsilon(\sigma)$ preserves the Weil-Petersson metric $\langle \cdot, \cdot \rangle$. From Wolpert's lecture note [23], we have

$$\langle \lambda_i, \lambda_j \rangle = \frac{1}{2\pi} \delta_{ij} + O(l_i^{3/2} l_j^{3/2}), \quad \text{for } \lambda_i = \text{grad} \sqrt{l_i}.$$

On $F^\varepsilon(\sigma)$, we have

$$\langle \lambda_i, \lambda_j \rangle = \frac{1}{2\pi} \delta_{ij} + O(\varepsilon^3),$$

because $l_i = l_j = \varepsilon$ on $F^\varepsilon(\sigma)$. $F^\varepsilon(\sigma)$ has twist coordinates $\tau_1, \dots, \tau_{3g-3}$. Wolpert's *twist-length duality* [23] asserts that

$$2t_i = J \text{grad } l_i,$$

where $2t_i$ is the Hamiltonian vector field (along τ_i) corresponding to dl_i .

Thus

$$t_i = \frac{1}{2} J \text{grad } l_i = \sqrt{\varepsilon} J \text{grad} \sqrt{l_i} = \sqrt{\varepsilon} J \lambda_i,$$

and

$$\left\langle \frac{t_i}{\sqrt{\varepsilon}}, \frac{t_j}{\sqrt{\varepsilon}} \right\rangle = \langle J \lambda_i J \lambda_j \rangle = \frac{1}{2\pi} \delta_{ij} + O(\varepsilon^3).$$

Therefore, the facet $F^\varepsilon(\sigma)$ together with the (normalized) Weil-Petersson metric

$$\frac{2\pi}{\varepsilon} \langle t_i, t_j \rangle = \delta_{ij} + O(\varepsilon^3)$$

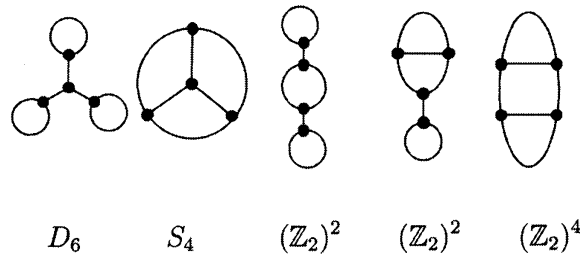
converges to Euclidean space \mathbb{E}^{3g-3} as $\varepsilon \rightarrow 0$, on which $NT(\sigma)$ acts as a crystallographic group.

In our case where σ is maximal, $W(\sigma)$ is a finite group. This group is nothing but the automorphism group of a finite trivalent graph (the pants graph, i.e., the dual graph of

the pants decomposition associated with σ). Conversely, given any finite trivalent graph, a crystallographic group appears exactly in the same manner as above.

The group $W(\sigma)$ is somewhat similar to the “Weyl group”, and a pants graph has an atomosphere of a “root system”. Details of this report will appear in [19].

Here are the trivalent graphs for $g = 3$ (with 4 vertices and 6 edges) and the corresponding point groups $\overline{NT}(\sigma)$ (n.b. not their groups $W(\sigma)$):



Acknowledgement: The author is grateful to Sumio Yamada for discussions and useful comments on the Weil-Petersson metric. Thanks are also due to Lizhen Ji who kindly informed the author of Ivanov’s work.

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